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Frictional sliding tests on combined coal-rock samples

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ABSTRACT

A test system was developed to understand the sliding mechanism of coal-rock structure. The test system was composed by a double-shear testing model and an acousto-optic monitoring system in association with a digital camera and an acoustic emission (AE) instrument. The tests can simulate the movement of activated faults and the sliding in coal-rock structure. In this regard, instable sliding conditions of coal-rock samples, sliding types under different conditions, displacement evolution law, and AE characteristics during sliding process were investigated. Several sliding types were monitored in the tests, including unstable continuous sliding, unstable discontinuous sliding, and stable sliding. The sliding types have close relation with the axial loads and loading rates. Larger axial load and smaller loading rate mean that unstable sliding is less likely to occur. The peak shear stress was positively correlated with the axial load when sliding occurred, whereas the displacement induced by unstable sliding was uncorrelated with the axial load. A large number of AE events occurred before sliding, and the AE rate decreased after stable sliding. The results show that the tests can well simulate the process of structural instability in a coal bump, and are helpful in the understanding of fault activation and the physical processes during squeezing process of roof and floor.

1. Introduction

Coal-rock is a kind of heterogeneous and anisotropic geo-material associated with significant nonlinear behavior and with discontinuous geological interfaces, including stratifications, joints, schistosity, and fractures, which divide the coal-rock into various structural blocks. Geological interfaces and structural blocks constitute the structure of coal-rock (Xie and Pariseau, 1993). Statistically, coal bumps usually occur in vicinity of fault zones, fold zones, or the areas that have experienced a major change in coal seam dip (Jiang et al., 2012; Zhao et al., 2013), thus the occurrence of coal bumps is related to the type of coal-rock structures in the area of interest. Also the dilatancy effect induced by compression of coal seams usually causes tensile stresses in the coal mass. When the coal mass is disturbed under quasi-static loading induced by mining, the coal-rock will slide out in blocks or as a whole, which is called coal bump of structure unstable type that is induced by coal-and-rock sliding (Jiang et al., 2009; Zhang et al., 2012).

Friction phenomenon exists in various scales of geological movement. The relative movement of the two walls of a fault is similar to stick-slip in form of friction, and stick-slip can be regarded as a factor causing tectonic earthquakes (Brace and Byerlee, 1966; Byerlee and Brace, 1968; Byerlee, 1970). In fact, a coal bump is usually caused by mining disturbance that induces fault activation (Ruina, 1983; Farmer, 1985). This unstable mode can be attributed to a stiffness difference between the coal seam, roof and floor, or by geological factors. In this case, it can be classified as a structural unstable coal bump. Research on the friction associated with a fault and the mining is important for understanding the mechanism of structural unstable coal bump.

In this context double-shear tests are important to understand the sliding mechanism of coal-rock structure. In the double-shear friction test, the contact area basically remained constant during the tests, making it easy to determine the stress state of the sliding surface. It should be noted that the test method is suitable when the normal stress is relatively low. However, a relatively large sliding displacement is allowed and can be directly measured. So the double-shear test method is chosen in this study (Price and Cosgrove, 1990).

The process of stick-slip, to a certain extent, is related to fault activation. As a result, many seismologists studied the mechanism

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of earthquakes by conducting friction tests on rocks (Brace and Byerlee, 1966; Ma et al., 2007; Song et al., 2012a; Passelègue et al., 2013). These tests were frequently observed in the field of seismicity, but the one associated with coal mining was rarely reported. In this paper, the friction-sliding experiments were conducted on coal-rock samples to simulate mining-induced fault activation and structural unstable coal bump, especially the squeezing of the roof and floor.

2. Experimental procedure

2.1. Experimental device and rock samples

The double-shear friction test was conducted imposing biaxial loads by an independent hydro-cylinder and a loading device in vertical and horizontal directions. The independent loads on two orthogonal directions can be applied. The rock samples include granite, sandstone, and coal (Fig. 1).

The testing model is shown in Fig. 1a and testing samples in Fig. 1b. The vertical loading direction was defined as the axial direction, and the horizontal loading direction as the shear direction. A constant axial load was specified, and the lateral load was increased stepwise till sliding of the samples. The loading steps were considered as follows: first, the axial stress was applied and increased to the desired value gradually. Once the desired value was reached, the axial stress was kept constant with the loading control method; then the shear stress was applied, with displacements control, to observe the occurrence of friction sliding. If any of the following conditions was reached, the test can be finished: (1) the sample was damaged; (2) unstable sliding occurred; or (3) the shear displacement was out of the limit of the testing apparatus. Before testing, the uniaxial compressive strength (UCS) was determined on rock samples with different lithologies. The sample parameters and basic experimental conditions are shown in Table 1.

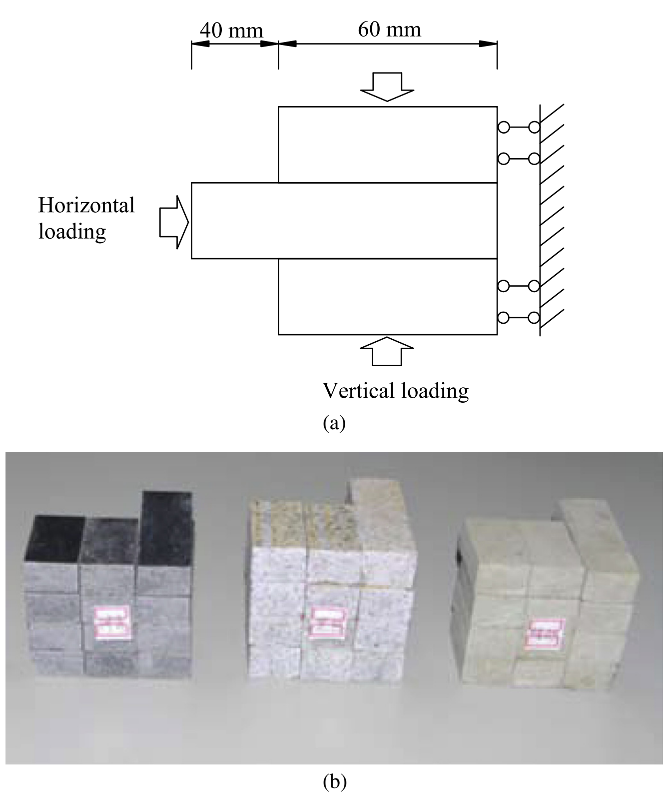

Fig. 1. Testing model and samples. (a) Testing model and (b) Testing samples.

2.2. Monitoring system

The experimental system and the displacement observation system are shown in Fig. 2. Digital speckle measuring points were arranged on the front surface to measure the sliding displacement, and two AE sensors were mounted on the rear surface of the sample to collect the information obtained by the AE sensors during sliding. Before test, the timing system was calibrated to ensure consistent measurement of different monitoring systems.

Digital photographic technology was used in the test to acquire visual information about the specimen surface, and the digital speckle correlation method was used to analyze the slip surface by examining the speckle displacement regularity and sliding characteristics. A 1351 μm Daheng-type industrial camera was used, and it was attached on a computer system for real-time image acquisition at a frequency of 15 fps.

An SWAES multichannel AE detector with full waveforms was used in testing. Its frequency ranges from 50 kHz to 400 kHz, and the resonance frequency is 150 kHz. The peak sensitivity is greater than 65 dB, and the pre-amplitude gain is 40 dB. The bandwidth range is 2–10 MHz, and the highest sampling rate of the acquisition card is 20 MHz. A number of analyses were performed based on ringing count and energy count (Lockner, 1993; Mansurov, 1994; Arasteh et al., 1997; Builo, 2000; Shkuratnik et al., 2004; Zhao and Jiang, 2010).

3. Friction sliding characteristics of coal-rock structure

Eight groups of rock specimens with four different lithologies were considered in the sliding friction tests. Unstable continuous sliding, unstable discontinuous sliding, and stable sliding were observed in the tests. The sliding rule was analyzed based on different sliding mechanisms.

3.1. Stress and AE characteristics during the process of unstable continuous sliding

An axial load of 20 MPa was applied on the granite specimen 1–5, and the shear loading rate was 0.25 mm/min. Unstable continuous sliding occurred several times in the form of regular stick-slip, followed by a rhythmic “click” sound. The shear stress curve is shown in Fig. 3, with the change in loading observed.

When the shear stress reached 6.05 MPa, the first unstable sliding event was recorded in the sample with a stress drop of 0.72 MPa. The changes of peak stress and stress drops are shown in Fig. 4, in association with the change in displacement.

It is obvious from Fig. 4 that the peak stresses of different unstable sliding events were linearly arranged. The friction strength of the rock samples increased with the increasing displacement. The peak stresses were increased by approximately 0.06 MPa from one unstable period to the next. The stress drops increase linearly at the beginning, but with small fluctuations in growth.

For the specimens under high stresses, small fractures occurred in the friction surface during the process of unstable sliding, which makes the friction surface roughly. The lubrication function of fragments made the stress drop curve fluctuate irregularly. This phenomenon is similar to that of a coal bump during coal mining. If several working faces cross the same fault and coal bumps occur at one working face, coal bumps with the same intensity are likely to occur at one of the other working faces at approximately the same position. After that, the chance of coal bump decreases at other working faces.

The shear stress curve and AE characteristics during unstable sliding are shown in Fig. 5, with which we can analyze the relationship between the sudden release of shear stress and AE count.